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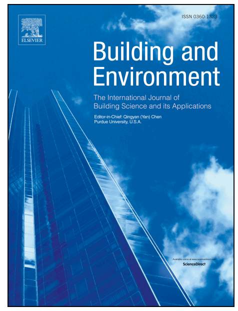

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PII: S0360-1323(14)00293-5

DOI: 10.1016/j.buildenv.2014.09.001

Reference: BAE 3817

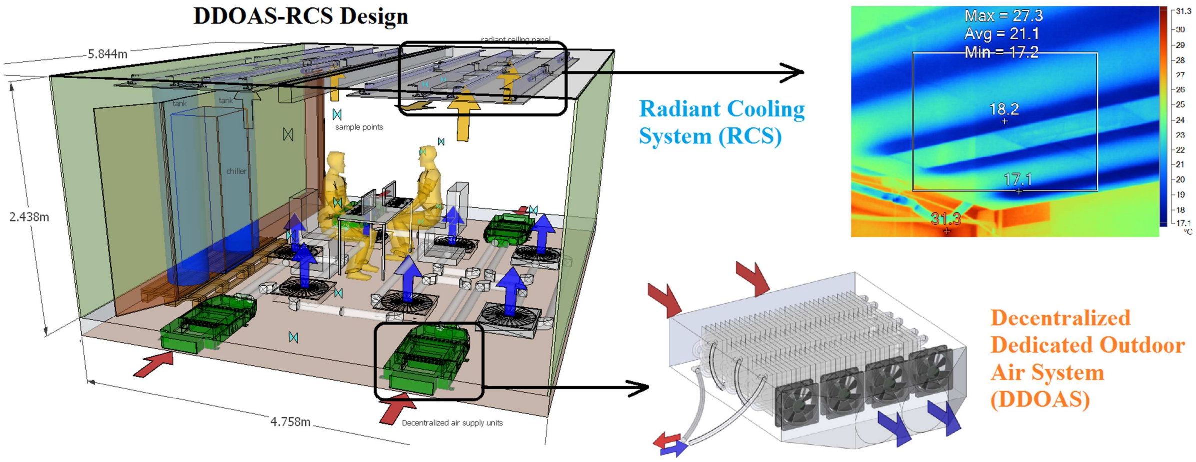
To appear in: *Building and Environment*

Received Date: 18 June 2014

Revised Date: 31 August 2014

Accepted Date: 1 September 2014

Please cite this article as: Saber E, Iyengar R, Mast M, Meggers F, Tham KW, Leibundgut H, Thermal comfort and IAQ analysis of a decentralized DOAS system coupled with radiant cooling for the tropics, *Building and Environment* (2014), doi: 10.1016/j.buildenv.2014.09.001.



DDOAS-RCS Design
5.844m
2.438m
4.758m
sample points
chiller
Decentralized air supply units
Radiant Cooling System (RCS)
Max = 27.3
Avg = 21.1
Min = 17.2
18.2
17.1
Decentralized Dedicated Outdoor Air System (DDOAS)

Thermal comfort and IAQ analysis of a decentralized DOAS system coupled with radiant cooling for the tropics

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Abstract
The deployment of low exergy concepts in buildings, which promotes high temperature cooling HVAC systems introduces alternative solutions in the tropical climate. This study evaluates the performance of a decentralized dedicated outdoor air system combined with a radiant cooling system (decentralized DOAS-RCS) in terms of occupant thermal comfort and indoor air quality for the tropical context. Different sets of operational scenarios (experiments) have been conducted in the BubbleZERO laboratory to realize the impact of system related parameters like ventilation rate and supply chilled water temperature on thermal comfort and indoor air quality. The results show that supply chilled water temperature and space cooling load have strong impacts respectively on the capacity of decentralized units and cooling panel, which consequently influence indoor air condition. Indoor air was predicted to be in comfort range (-0.2 < PMV < 0.2) only at specific periods of the day and an automatic control was required to modulate the system under various indoor and outdoor conditions. Main challenges of implementing DDOAS coupled with radiant cooling in the tropics include the condensation risk on the radiant panels, non-uniformity of panel surface temperature and low air movement inside the space.

Keywords – Low Exergy, Thermal Comfort, Indoor Air Quality, Decentralized Dedicated Outdoor Air System, Radiant Cooling system

1. Nomenclature

AHU	Air Handling Unit
BubbleZERO	Bubble-Zero Emission Research Operation
CFD	Computational Fluid Dynamics
clo	Clothing Unit
COP	Coefficient of Performance
DCV	Demand Control Ventilation
DDOAS	Decentralized Dedicated Outdoor Air System
DOAS	Dedicated Outdoor Air System
I_{cl}	Clothing Insulation (m^2 K/W)
M	Metabolic Rate (W/m^2)
met	Metabolic Unit
PM_1	Particulate Matter Less than 1 μm
$PM_{2.5}$	Particulate Matter Less than 2.5 μm
PM_{10}	Particulate Matter Less than 10 μm
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
RCS	Radiant Cooling System
RSP	Respirable Suspended Particles
SHR	Sensible Heat Ratio
SS	Singapore Standards
t_a	Dry Bulb Temperature
t_d	Dew point Temperature
$\overline{t_r}$	Mean Radiant Temperature
T_s	Surface Temperature
TVOCs	Total Volatile Organic Compounds
UFAD	Under Floor Air Ducting
v_{ar}	Air Velocity
VAV	Variable Air Volume

2. Introduction

Cooling and dehumidification cause the biggest portion of energy usage in commercial buildings in the tropical maritime climates. In conventional central air conditioning system, fresh and return air streams are mixed, conditioned and supplied to satisfy both sensible and latent loads of the building. An alternative technology is DOAS (Dedicated Outdoor Air System) where 100 % fresh air is brought into the space to satisfy latent load, ventilation requirement, and part of space sensible load. A parallel radiant cooling system like radiant ceiling panel or active/passive chilled beam can be employed to handle the remaining sensible load. This separation increases the share of water as the heat transport media in the air conditioning system of buildings. It also facilitates the use of demand control ventilation (DCV) system by deploying carbon dioxide sensors in indoor space. The main advantages of DOAS compared to conventional all air system are less noise, lower air draft, and better thermal comfort for occupants achieved by radiative heat transfer and also potentially less energy consumption. DOAS can save energy through using water as heat carrier to lower energy usage related to air transport. It also allows reducing duct size since they only cater for the outdoor air intake. In addition, the parallel radiant system is categorized as a high temperature cooling systems, which can lead to a higher coefficient of performance (COP) of the refrigeration cycle.

In the literature, different amounts of savings, compared to central DOAS, have been reported for different climates. Mumma [1] has done an hourly energy analysis for the humid continental climate of Philadelphia and showed conventional VAV (Variable Air Volume) systems to cost about 29 % more to operate compared to radiant cooling/DOAS. Tian and Love [2] have done an energy performance analysis for different climates, ranging from cold and dry to very hot and humid, and showed that radiant slab cooling/DOAS has a 10-40 % higher energy performance, depending on the climate types. Risk of condensation on panels is the main concern of using radiant cooling panel in the tropical climates with high humidity level all year around. With control of humidity level in conditioned space and keeping dew point below panel surface temperature, the condensation risk can be avoided. Mumma [3] has shown that even if the humidity level exceeds the threshold, it could take hours for condensation thickness on panel to equal the diameter of the human hair. However, this was observed in a climate with humidity levels lower than that of maritime tropical climate. The other comfort concern of DOAS/radiant cooling is lower air movement (compared to the conventional all air system), which does not satisfy the requirement of local standard (in range of 0.1 - 0.3 m/s based on SS 554). In DOAS design, though the lower air movement is compensated by lower mean radiant temperature in space, response and adaptation of occupants in the tropics to this new indoor environment should be investigated through a subjective study. In a relevant subjective study, Chiang et al. [4] analyzed the combination of ceiling cooling and displacement ventilation for subtropical regions of Taiwan and found the lower air movement (air velocity in range of 0.01 - 0.16 m/s), an advantage of this design to prevent draft. In similar studies on the application of radiant cooling in subtropical and tropical climates of Pakistan, Thailand and Indonesia, higher surface panel temperature has been used to avoid condensation while occupants have been adapted to higher indoor temperature condition than ASHRAE 55 standard [5–7]. In a review paper, De Dear et al. [8] reviewed the trend of thermal comfort studies in last two decades and they observed the paradigm shift from heat-balanced thermal comfort models toward adaptive models.

Chen and Chang [9] investigated the overcooling perception of office workers in Singapore and the results showed that the average indoor temperature of 24.5, which is in-line with the PMV model, is too cold as expressed by actual occupants' thermal sensation vote. However, Willem and Tham [10] showed that tropically acclimatized subjects prefer a neutral to slightly cool thermal sensation, which is optimized when the thermal sensation was -0.4. In another field study in high rise public housing in Singapore, De Dear and Leow [11] found that acclimatized human in the tropics prefer 2 °C warmer temperatures than the value predicted by the PMV model and ISO standard. Regarding the impact of air movement, Gong et al. showed that more than 30 % of locally acclimatized people in the tropics still prefer higher air movement even at local temperature of 23.5 °C and local air velocity of 0.15 m/s. Overall, the majority of research results in the literature showed that the PMV model fails to predict the actual response of acclimatized occupants in the tropics especially for naturally ventilated spaces. However, for conditioned spaces in the tropics, slightly warmer neutral temperatures compared to PMV prediction have been reported and this difference ranges from 0 to 2 °C. However, one study even reported that a slightly cooler temperature is preferred by local occupants [10–14]. Based on these studies, it can be concluded that the PMV model can be used as a conservative lower boundary to predict occupant satisfaction in conditioned spaces in the tropics.

The objective of this study was to evaluate the performance of a new designed decentralized DOAS concept coupled with radiant cooling panels for the tropics in terms of thermal comfort and indoor air quality. Different sets of experiment were conducted in the test bed of low exergy ventilation technologies (BubbleZERO) in Singapore. The goal was to realize the impact of system related parameters like ventilation rate and chilled water temperature on thermal comfort and indoor air quality of the conditioned space. Environmental parameters like dry bulb temperature, mean radiant temperature, and humidity level were measured at different locations of the BubbleZERO as well as air pollutants like CO_2, VOCs and fine particles. The results were analyzed based on thermal comfort and indoor air quality criteria of local and international standards as well as a thermal comfort model.

3. Background

Low exergy ventilation technologies including decentralized air supply units and radiant ceiling panel have been designed by the LowEx team in ETH, Zurich first for the continental climate of Zurich and then modified for the tropical climate of Singapore [15–17]. These technologies have been implemented in a laboratory called BubbleZERO which has been located near the campus of NUS [18]. In the BubbleZERO, the DOAS concept has been deployed in an innovative way by using decentralized units, which will subsequently be referred to as Decentralized DOAS (DDOAS). Decentralized air supply units embedded into the structure of a building could bring in enough fresh air through the façade and dehumidify it to keep the dew point of the air within the space below the radiant panel surface temperature to avoid condensation. The amount of supplied fresh air in DDOAS-RCS varies based on the latent load and ventilation requirement of the space. Minimum requirements of standards need to be considered and can be accompanied by monitoring indicators of indoor air quality such as CO2. An additional consideration is the need to achieve adequate air movement as occupants in the tropics prefer higher air movement in conditioned spaces [19]. However, reported energy breakdown of HVAC systems for commercial buildings in the literature revealed the significantly higher energy use of supply, return and exhaust fans compared to chilled water pumps [20,21]. It can be concluded that the transport of chilled water in a building is less energy intensive compared to the transport of cool air and there is potential to reduce energy consumption by replacing all air systems with air/water systems. However, this change could increase the investment and maintenance cost of HVAC system and a life cycle analysis at design stage should be conducted to evaluate the overall benefits.

The concept of DDOAS has been developed to reduce energy use related to air transport and air duct size compared to centralized DOAS by bringing chilled water closer to the conditioned space. Instead of several air handling units (AHUs) for each floor many decentralized air supply units can be embedded into the structure of a building to take fresh air directly from the façade. Decentralized units are installed on different facades (single or multi directional) to accommodate shortest and least energy intensive way of supplying fresh air to the conditioned space. The higher number of fresh air intakes on the façade increase the chance of the exposure to direct sunshine or wind flow and severity of these impacts on the operation of DDOAS-RCS depends on the type of climate. The issue of sunshine exposure can be effectively resolved by using proper external shadings over the air intake points. The median cloud cover of Singapore is 90 % and it is less likely to be a serious issue for this climate. In addition, Singapore is a low wind territory and wind speed does not play any significant role on operation of cooling system of buildings. For windy locations and implementations in tall buildings, the wind pressure can have some impact and needs to be taken into account at design stage of system. In this design of DDOAS-RCS, air is supplied to the indoor space through an under floor interlaced ducting system to take advantage of displacement ventilation (DV) strategy. The interlaced ducting system is considered to provide an uniform air supply to the whole floor under non-uniform air pressure of air intakes on different facades. Another rationale for using interlaced ducting network is the potential integration into concrete floor slab. Dissatisfaction of occupants due to the excess thermal stratification in the space is one of the drawbacks of DV strategies, which needs to be taken care of at design stage. The schematic overview of DDOAS-RCS installed in the BubbleZERO including the two chillers and tanks is shown in Fig. 1. By implementing this design, floor to floor height could be considerably decreased and AHU rooms in buildings could become obsolete. In a typical space with DV cooling concept, space is divided into lower clean zone and upper contaminated zone so less air needs to be conditioned and it is preferred over mixing ventilation for tall and high volume spaces (e.g. theatres). However, current distribution of DDOAS-RCS is a low speed UFAD combined with chilled ceiling in which cooling happens from both floor and ceiling. In this combination, the interaction of RCS and DDOAS brings complexity into design and control of this cooling system and it needs to be investigated on a case by case basis. In general, when the sensible cooling load of a building is low, the required fresh air supplied by DDOAS could satisfy both latent and sensible loads. However, when the sensible load is beyond a limit, conditioned fresh air is not sufficient to handle the whole sensible load, and in this case a parallel radiant system can be employed. Attention during the design of the combined system needs to be given to mitigate condensation risks. The combination of decentralized dedicated outdoor air system and radiant cooling system is referred to as DDOAS-RCS which has been investigated in this study.

Fig. 1 here

4. Research Methodology

The main space related parameters, which affect thermal comfort and air quality of DDOAS-RCS, are fresh air flow rate (ventilation rate), air supply temperature, humidity level, and radiant panel surface temperature. The modular control system of chillers, pumps and decentralized units in the BubbleZERO test bed provided the opportunity to assess the impact of these parameters as a function of system related parameters and outdoor condition. Different scenarios of ventilation rate, chilled water temperature and human load in the space have been experimentally evaluated to provide a better understanding of the impact of each factor. The range of system and space related parameters, which were investigated in this study, are listed in Table 1. These operational parameters of the system and the occupancy pattern can affect thermal comfort and indoor air quality of the conditioned space so their sensitivity had to be determined. The range of values for each parameter has been chosen based on preliminary experiments, which have been conducted to achieve acceptable air condition in the BubbleZERO for a typical cloudy day. In this paper, the daily profile of indoor air and system parameters provided for a typical cloudy day since the median cloud cover of Singapore is 90% over the year. For this typical scenario, the dry blub and dew point temperatures range between 27 to 33 °C and 23 to 25 °C, respectively in which the peak cooling load happens around 5 pm. Singapore is a low level wind territory with outdoor wind speed usually ranging between 1 to 6 m/s which does not play a significant role on the operation of the building cooling system for an indoor controlled environment. Illustrations of the technologies installed in the BubbleZERO including the locations of sample points and seated occupants are shown in Fig. 2. Since the lab is located outdoors and its façade is exposed to direct sunshine and rainwater, the space has been conditioned continuously for several days prior to the experiments to get rid of stored heat and humidity in the façade materials. The experiments have been conducted for several weeks in March-April 2014, which can be representative of all year since Singapore has a tropical rainforest climate with almost similar ambient conditions all year around.

Table 1 Ranges of system and space related parameters

System components	**Parameters**	**Range of values**
Decentralized ventilation units	4 units (2 on east façade, 2 on west façade) supply air through 7 floor diffusers	W×L×H (40 cm × 50 cm × 10 cm)
	Cooling capacity of each unit	600-1500 W
	Ventilation rate (all units)	1.03-1.42 L/s/m^2
	Chilled water supply temperature	8-14 °C
Radiant cooling panel	2 radiant panels attached to the ceiling	net cooling surface area of each 7 m^2
	Cooling capacity of each panel	60-300 W (9-43 W/m^2)
	Panel surface temperature	18-22 °C
	Chilled water supply temperature	17-19 °C
Space Related parameters		
	Insulated on North and South with glass façades on East and West	25 m^2 floor area
Human load	Occupants sitting in the center of room performing office activity	1-2 (0.1-0.2 person/m^2)

Fig. 2 here

Environmental parameters like dry bulb temperature, mean radiant temperature, relative humidity and also human related pollutants of CO_2 are measured continuously throughout the experiments. In addition to these continuous measurements, spot measurements have been conducted for other indoor air pollutants like volatile organic compounds (VOCs) and respirable suspended particles (RSP). Continuous and spot measuring instruments which have been used for the experiments are listed in Table 2, including their accuracy and resolution. The duration and location of sensors deployment are also mentioned in Table 2. Environmental parameters like temperature and humidity were continuously measured at different points and heights inside the space and outside. However, indoor air pollutants like RSP and TVOCs were only measured at several spots during the experiments. The goal of the measurements was to qualitatively identify any potential IAQ risk but not to quantitatively monitor potential pollutants. Since the results were much lower than the threshold values set by Standards SS 554, It was deemed sufficient to measure in several spots. The environmental parameters related to the thermal comfort of occupants including dry bulb temperature, relative humidity, air velocity, clothing level and metabolic rate have been chosen to get a better understanding of spatial distribution of these parameters. Among the indoor air pollutants, RSP and TVOCs were measured to evaluate the concerns of particle entrainment to the breathing zone by UFAD and the possible emission of organic compounds inside the space.

In the second part of this paper, recorded data have been evaluated against Singapore standards SS 553 [22] and SS 554 [23], International standards ISO 7730 [24], ASHRAE 55 [7] and also Fanger's thermal comfort model. As discussed in the Introduction section, different expectation of thermal comfort of tropically-acclimatized occupants, has been identified as a source of inaccurate prediction of Fanger's PMV model by many studies [25,26]. However, for conditioned spaces in the tropics, there are mixed results and conclusions in the literature and overall PMV predictions seem to be close to the actual perception of occupants in conditioned spaces.

Table 2 Measuring instruments and their technical details

Parameters & Pollutants	Measuring Instruments	Accuracy/ Resolution	Duration - Location
Respirable Suspended Particles (RSP), PM_1, $PM_{2.5}$, PM_{10}	DUSTTRAK™ DRX Aerosol Monitors Models 8533	**Res.**: ±0.1 % of reading or 0.001 mg/m3, whichever is greater	Spot measurements - several points
Carbon Dioxide, CO_2	IAQ-CALC™ Indoor Air Quality Meters Model 7545	**Acc.**: ±3.0 % of reading or ±50 ppm, whichever is greater **Res.**: 1 ppm	Continuous and spot measurements - several points
Total Volatile Organic Compounds (VOCs)	Portable Handheld VOC Monitor- ppbRAE 3000	**Res.**: 1 ppb	Spot measurements - several points
Indoor Air Velocity, v_{ar}	Kanomax Anemomaster Model A031 Series	**Acc.**: ± 2 % of reading or ± 0.015m/s whichever is greater **Res.**: 0.01m/s	Spot measurements - several points
Surface Temperature, T_s	Fluke Dual Input Contact Digital Thermometer 54-ii	**Acc.**: ± 0.05 % of reading ± 0.3 °C	Spot measurements - Interior surfaces
Surface Temperature, T_s	Fluke Building Diagnostic Thermal Imagers Models: TiR32, IR fusion technology	**Acc.**: ± 2 °C or 2 % (at 25 °C nominal, whichever is greater)	Spot measurements - Interior surfaces
Mean Radiant Temperature, $\overline{t_r}$	Globothermometer BabucA	**Acc.**: ± 0.14 °C **Res.**: ± 0.01 °C	Continuous measurements - several points
Air Temperature, t_a Relative Humidity RH, Dew Point t_d [1]	Onset HOBO data loggers U12	**Acc.**: ± 0.35 °C, ± 3.5 %RH **Res.**: ± 0.03 °C, ± 0.03 %RH	Continuous measurements - different heights in the space

[1] Propagated uncertainty in calculated dew point temperature from dry bulb temperature and relative humidity is ± 1.3 °C

5. Results & Discussions

5.1 Decentralized Air Supply Units

In a DDOAS-RCS combination as implemented in the BubbleZERO, the most important role of decentralized air supply units is humidity control and ventilation. Therefore, they have a strong impact on indoor air quality and the energy consumption of the whole system. From the energy efficiency point of view, the amount of fresh air should be minimized and kept close to the minimum ventilation requirement of the space. Regarding air quality at occupant level, air distribution effectiveness of the under floor distribution system in the BubbleZERO would determine this minimum ventilation requirement and influence thermally driven forces around the human bodies. In addition to purging of pollutants from the occupant zone, the supplied fresh air should satisfy latent load of space; so having an air tight façade is a necessity for this design to minimize the amount of latent load in space. By integration of demand controlled ventilation (DCV) the right amount of fresh air could be supplied into the indoor space based on CO_2 sensor data as a proxy of occupant level.

Three heat exchangers with different hydronic connections of the heat exchangers have been incorporated into the decentralized air supply units. Unmixed cross-flow heat exchangers were used in which hot and humid air flow passing across tubes carrying chilled water. The circuiting arrangement of these cooling coils affects their cooling and dehumidification capacity and subsequently the condition of the supplied air. Different adjustments of supply and return water to and from cooling coils inside the units have been evaluated in a previous set of experiments [27]. The results have shown that a counter flow arrangement of streams in the units provides the highest capacity compared to other arrangements. In this arrangement supply chilled water feeds into the last heat exchanger and after passing through three coils, it leaves the first heat exchanger near the hot and humid entering air. The capacity of these decentralized units for a typical cloudy day with fluctuating supply chilled water temperature is shown in Fig. 3. The fluctuation in supply water temperature, which was caused by the chiller's control settings, provides an observation of the impact of chilled water temperature on the units' capacity. For chilled water in the range of 8 to 14 °C, the capacity of units ranges between 600 to 1500 W and the maximum value occurs in the afternoon (around 3-6 pm). The difference between supply and return water temperatures ranges between 5 to 8 °C and this value is higher for lower supply water temperatures. These results show the strong impact of chilled water temperatures on the capacity of decentralized units. The outdoor conditions, to a lesser degree, impact the capacity as well. The Singapore outdoor design condition is 33 °C dry bulb and 26 °C wet bulb temperatures and these decentralized units have been designed to cool and dehumidify it to achieve saturated air of 12-14 °C after passing the cooling coils. Outdoor conditions are usually lower than the design values and the chilled water flow rate to the units therefore needs to be controlled based on the indoor and outdoor conditions.

Fig. 3 here

5.2 Radiant Cooling Panel

Radiant ceiling panel is the parallel sensible cooling system, which has been chosen for the decentralized DOAS-RCS system. Two multifunctional ceiling panels with integrated LED lighting, CO_2-sensor controlled exhaust flaps and integrated exhaust ducts have been implemented in the BubbleZERO. Decentralized air supply units satisfy the ventilation requirement, latent load and part of the space sensible load, while radiant ceiling panels satisfy the remaining sensible load. Panel surface temperature should be set in a way to avoid condensation and at the same time provide enough cooling capacity to satisfy the portion of space sensible load not met by the DDOAS. In general, heat transfer between a panel and the conditioned interior happens mostly through radiant heat transfer to other surfaces in the space and partly through convection with surrounding air. The driving force for the radiative heat transfer, based on the Stefan-Boltzmann law, is the difference between fourth power of the absolute temperature of the panel and body and view factor of the panel surface to the other interior surfaces. This temperature difference can be seen in infrared images as presented in Fig. 4. This image has been taken inside the space for a typical cloudy day around 3 pm. As can be seen in this infrared image, the temperature of those areas of the panel which are in contact with hydronic water pipes is considerably lower than the remaining areas. In order to obtain accurate surface temperature readings, a digital contact thermometer has been used in addition to an infrared camera during the experiments (Fig. 5).

Fig. 4 here

One of the common problems associated with radiant panels is the non-uniformity of the panel surface temperature. A typical temperature distribution over the whole panel surface with LED lights switched ON is shown in Fig. 5. The surface temperatures change from time to time because of the fluctuation in supply water temperature and cooling load of the space. However, the relative difference of surface temperature between surface zones remains in the same range. For this panel, the areas of minimum temperature are near the supply water pipes (17 °C) whereas the areas of maximum temperature are close to the integrated LED lights (34 °C). The temperature variation over the rest of the panel, except for the middle part, depends on the location of the hydronic pipes and the sensible cooling load of the space. In the current two-pass configuration of the hydronic pipes, the area below water pipes is 1 to 3 °C colder than the rest of the panel. Therefore, increasing the number of cold water passes could improve uniformity of surface temperatures and also enhance the cooling capacity per surface area. It is notable that in this multifunctional panel, the back of the LED lights form part of the exhaust duct. Thereby, part of the generated heat is directly transferred to the exhaust air.

Fig. 5 here

A daily profile of one radiant ceiling panel's (for one side of the lab) capacity with fluctuating supply water temperature for a typical cloudy day is shown in Fig. 6. The supply water temperature fluctuates frequently in the morning due to lower sensible cooling loads of space during that period and the chiller's non-modulating ON/OFF control setting. The capacity of the panel ranges between 60 to 250 W (9-36 W/m^2) in the morning while the supply water temperature ranges between 17 to 19 °C. In the afternoon, the panel capacity is around 300 W (43 W/m^2) even when the supplied water temperature is around 19 °C. This is due to the larger radiant heat exchange with the warmed up surfaces of the BubbleZERO. This observation shows the strong impact of the sensible cooling load resulting from the warmer interior surfaces on the panel capacity, which is more pronounced than the impact of the supply water temperature. This contrasts the behavior of the decentralized units, which has been discussed in the previous section. The difference between supply and return water temperature is between 1 to 2 °C and this value is higher for lower supply water temperatures.

Fig. 6 here

5.3 Decentralized DOAS combined with Radiant Cooling (DDOAS-RCS)

Different set of experiments have been conducted at the BubbleZERO test bed under various operational scenarios of DOAS-RCS for several days for each case. Environmental parameters including, dry bulb temperature, mean radiant temperature and relative humidity have been monitored and recorded at different locations inside the lab. The measured dry bulb temperature at heights of 10 cm, 100 cm, and 180 cm inside the space and also the outdoor air temperature are plotted in Fig. 7. The depicted internal air temperatures are average values of 4 sensors at each height. The data is shown for eleven consecutive days in which the ventilation rate was reduced from 1.42 to 1.03 L/s/m^2. This range of ventilation rates is 70 to 140 % more than the minimum ventilation requirement of office buildings in Singapore (0.6 L/s/m^2 based on SS 553 [22]). This reduction of fresh air flow rate, through changes of the fan speed of the ventilation units, decreased the cooling capacity of these units which caused a one degree increase of space temperature at the same outdoor condition (as shown in Fig. 7). It was also observed that a vertical thermal stratification of 2 °C occurred in the space and that this temperature gradient is steeper below a height level of 1 m.

Fig. 7 here

Dew point temperature (humidity level) and mean radiant temperature were also continuously measured at different locations inside the lab. The temperatures values for a typical cloudy day, including the calculated operative temperature, are plotted in Fig. 8. Mean radiant temperature is roughly 2 °C lower than dry bulb temperature in areas below the ceiling panels due to the impact of radiant cooling. The mean radiant temperature follows the same trend as the dry bulb temperature with peaks occurring in the afternoon. Under fixed operational scenario, the maximum dew point temperature occurs around 5 pm as well as dry bulb temperature. However the variation in dew point temperatures is lower than the change in dry bulb temperatures from morning till afternoon.

Fig. 8 here

The capacity of decentralized air supply units and radiant cooling panels was monitored during the experiments to identify the contribution of each part towards satisfying the sensible and latent loads of the space. The sensible and latent capacity ratio of the air supply units and radiant panels for a typical cloudy day are shown in Fig. 9. The curves generated based on the moving average trendlines of fluctuating capacities measured on decentralized units and radiant panels. It can be seen that in the morning, the sensible cooling capacity of units is higher than panel while in the afternoon both have an almost equal share in removing the sensible load of the space. For a typical cloudy day with no extensive rain, the maximum cooling load happens in the afternoon with a sensible heat ratio (SHR) of 0.6. The latent load of the space does not change that much during the day because of constant humidity levels in the outdoor air.

Fig. 9 here

6. Thermal Comfort and IAQ Evaluation

6.1 Thermal Comfort

Thermal comfort index and indoor air pollutants level are the main parameters, which should be evaluated for any air-conditioned building. DDOAS-RCS in tropics introduces a different indoor environment with lower air movement and mean radiant temperature compared to the conventional all air system. As shown in Fig. 9, the measured mean radiant temperature in the lab was roughly 2 °C less than dry bulb temperature at locations below the radiant panels. While Fanger's PMV model has not been fully accepted as a reference thermal comfort model for the tropical climates, it can provide insights into the possible range of acceptable indoor air conditions. Categories of A and B of thermal environment as specified by ISO 7730 [24] have been chosen as thresholds which respectively corresponds to -0.2 < PMV < 0.2 and -0.5 < PMV < 0.5 (Predicted Percentage Dissatisfied (PPD) < 6 and 10 %). The calculated PMV for a typical cloudy day inside the lab conditioned with DDOAS-RCS is shown in Fig. 10. PMV has been calculated for a normal male office worker with sedentary activity (1.2 met), long trousers and long sleeves shirt (0.79 clo). 1 met is the metabolic unit which is equal to metabolic rate (M) of 58.2 W/m^2 and 1 clo is the clothing unit which is equal to clothing insulation (I_{cl}) of 0.155 m^2 K/W. It can be seen in Fig. 8 that with fixed operational settings of the system (to satisfy maximum cooling load in the afternoon), the indoor air would be slightly overcooled in the morning but would eventually reach the comfort range in the afternoon.

The local discomfort criteria of categories A and B in ISO 7730 includes draft risk (maximum air velocity), vertical air temperature difference, range of floor temperature, and radiant temperature asymmetry. Draft risk is not a concern for this design because of low air movement and the vertical temperature difference or head to ankle temperature difference is less than 2 °C, which is in the acceptable range of both categories (A: < 2 °C, B: < 3 °C). The floor temperature of DDOAS-RCS ranges between 20-22 °C which is within the tolerable range specified by the standard (19-29 °C). In addition, the maximum measured surface temperature difference inside the lab was around 10 °C, which is less than the radiant temperature asymmetry threshold set by the ISO standard for cool ceilings (< 14 °C). Spot measurements with an anemometer revealed that the indoor air velocity is less than 0.01 m/s (resolution of device) in all locations except near the diffusers which is below the acceptable range of 0.1-0.3 m/s set by Singapore standard SS 554. While the calculated PMV shows that lower dry bulb and mean radiant temperature could compensate the impact of lower air movement, the preference of locally acclimatized occupants in the tropics has not been considered here.

Fig. 10 here

6.2 IAQ Evaluation

Other than overall and local thermal comfort of occupants, indoor air is also an important aspect of ventilation system design. Continuous and spot measurements of the main indoor air pollutants of carbon dioxide (CO_2), total volatile organic compounds (TVOCs) and respirable suspended particles (RSP) have been performed during the experiments. The measured CO_2 concentration during office hours (9 AM to 6 PM) under various ventilation rates and two occupancy levels (low: less than 0.1 person/m^2, medium: 0.2 person/m^2) are plotted in Fig. 11. The average value and the variation of the recorded concentrations during occupancy of the lab are shown in this graph. Depends on the experimental scenarios, one or two persons were asked to sit in the lab and engage in an office activity for several hours (9 AM to 6 PM). The details of the locations and posture of the seated humans are illustrated in Fig. 2. The ventilation rate ranged between 1.03 to 1.42 L/s/m^2, which is 70 to 140 % above the minimum requirements of 0.6 L/s/m^2 set by SS 553 for office buildings. As can be seen in Fig. 11, CO_2 level is below the threshold of 1100 ppm, corresponding to 700 ppm above the outdoor concentration (SS 554) in all the cases. The measured concentration is closest to the threshold value for a ventilation rate of 1.03 L/s/m^2 under medium occupancy. These results show that for actual design of a DDOAS-RCS in a real building, it would be a good practice to have fresh air flow rate at least 70 % above the minimum ventilation requirement of SS 553 in order to keep CO_2 level below the threshold value even for dense occupancy patterns.

Fig. 11 here

In addition, TVOCs concentrations have been measured at several spots in the laboratory. The observed values were around 150 ppb, which is well below the limit of SS 554 (3000 ppb). This measured concentration range shows that there is no concern regarding to organic compounds emitted from materials of walls, floor, roof, tables and other objects in the space. Furthermore, RSP concentrations have been measured for several hours. The maximum reported value during the sampling period was around 30 μg/m^3, which is bellow SS 554 standard limit (50 μg/m^3 for PM_{10}). This shows that there is no risk of suspended particles from the floor being stirred up by the air supplied from the under floor supply diffusers. The amount of air supplied by DOAS-RCS is about 20% to 40% of that supplied in a conventional UFAD system. This lower air movement results in lower risk in terms of particle dispersion in space, the problem which is associated with conventional UFAD design.

7. Conclusion

In this paper, the performance of a DDOAS-RCS design (decentralized DOAS coupled with radiant cooling system) in the tropics has been evaluated in terms of thermal comfort and air quality. Various sets of experiments have been conducted in a test bed called BubbleZERO in which the concept of DDOAS-RCS has been implemented. The impact of various system related parameters like ventilation rate, supply water temperature to radiant ceiling panel and decentralized units, and also human load on indoor air condition were investigated. Characteristics of the space conditioned with DDOAS-RCS were analyzed based on the criteria set by international and local standards and a thermal comfort model was implemented. The outcomes can be summarized in the following points:

- In DDOAS-RCS design, the chilled water temperature supplied to the decentralized ventilation units has a strong impact on the capacity of these units and therefore on the supply air conditions. The cooling capacity of decentralized units also increases slightly when they are operated under higher outdoor air temperature, demonstrating its design-responsiveness.
- The sensible cooling load of the space has a strong impact on the cooling capacity of radiant ceiling panels. This factor has a stronger impact than the supply water temperature to panels, especially in the afternoon, because of the radiative heat transfer between warm façade surfaces and cool ceiling panels.
- Non-uniformity of panel surface temperature, which is a common problem in radiant cooling panels, has been observed in the experiments. This could be mitigated by increasing the number of chilled water passes behind the panel.
- The low air flow rates lead to imperceptible air movement, which violates the requirements postulated by Singapore standard SS 554.
- For a certain range of ventilation rates, a reduction of supplied fresh air flow rate does not have a considerable influence on the air temperature of the conditioned space (1 °C increase with 30 % reduction of ventilation rate). However, to keep CO_2 level within the limits set by air quality

standards, ventilation rate should be at least 70 % above the minimum ventilation requirements of local standard (SS 553).

- Under fixed operational setting of DDOAS-RCS, thermal comfort, as described by the PMV model, can be achieved only for a specific period of time during a day. An automatic control of the system is required to modulate the capacity of the ventilation units and radiant ceiling panel under various indoor and outdoor conditions.

This study did not consider the impact of heavy rains or thunderstorms, which infrequently occur in the tropical climate of Singapore, on the system. In future works, these measurements would be accompanied by CFD (Computational Fluid Dynamics) modelling to get a better understanding of the influence and sensibility of system and space related parameters on thermal comfort and indoor air quality of conditioned spaces with DDOAS-RCS. In addition, further studies are required to determine whether the imperceptible air movement has a negative impact on the perception of such air conditioning systems by locally acclimatized occupants. In order to reveal the overall benefits of DDOAS-RCS compared to conventional all air system, an economic analysis is required. Life cycle analysis of this design needs an accurate energy analysis for a real case study of a specific configuration and climate type accompanied with the cost database of decentralized units, radiant panel, piping, required maintenance service, material saving due to the lower floor to floor height and leasable floor area.

8. Acknowledgment

This work was established at the Singapore-ETH Centre for Global Environmental Sustainability (SEC), co-funded by the Singapore National Research Foundation (NRF) and ETH Zurich. We would like to thank the other members of our team, Prof. Dr. Arno Schlueter (Low Exergy Module leader), Li Cheng (design of wireless sensor network), Marcel Brülisauer (construction of lab), Chen Kian Wee (architectural design of lab) and also acknowledge the generous help of the executives of IAQ, thermal and wind tunnel labs at the Department of Building of NUS. Finally, we would like to thank Simon Thomas and the United World College of South East Asia for hosting the BubbleZERO laboratory.

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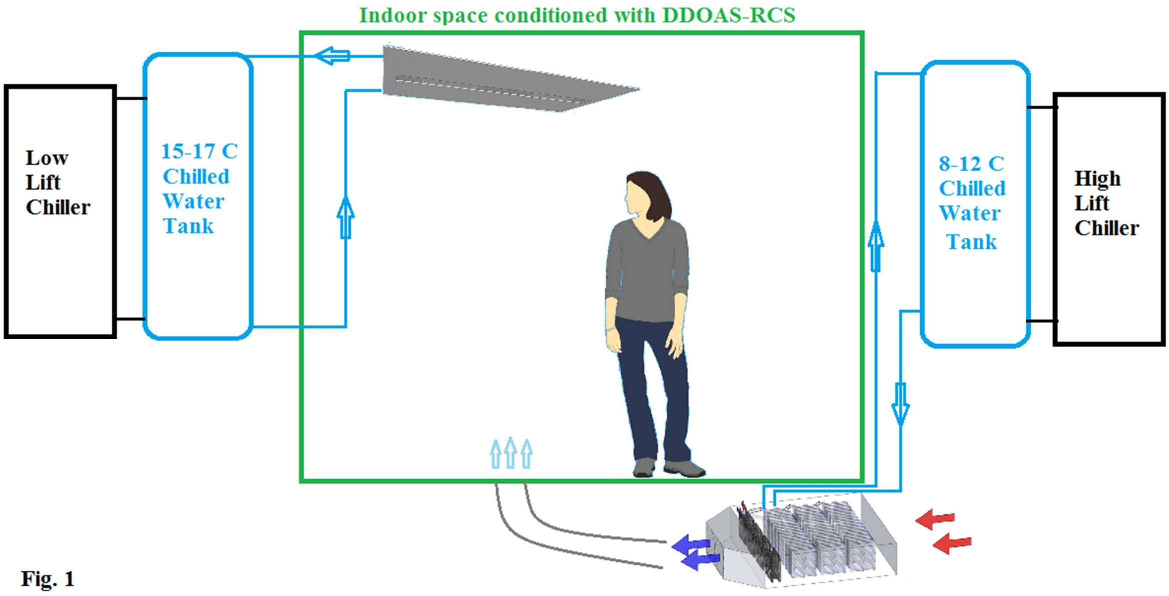
List of Figures:



Indoor space conditioned with DDOAS-RCS
Low Lift Chiller
15-17 C Chilled Water Tank
8-12 C Chilled Water Tank
High Lift Chiller

Fig. 1

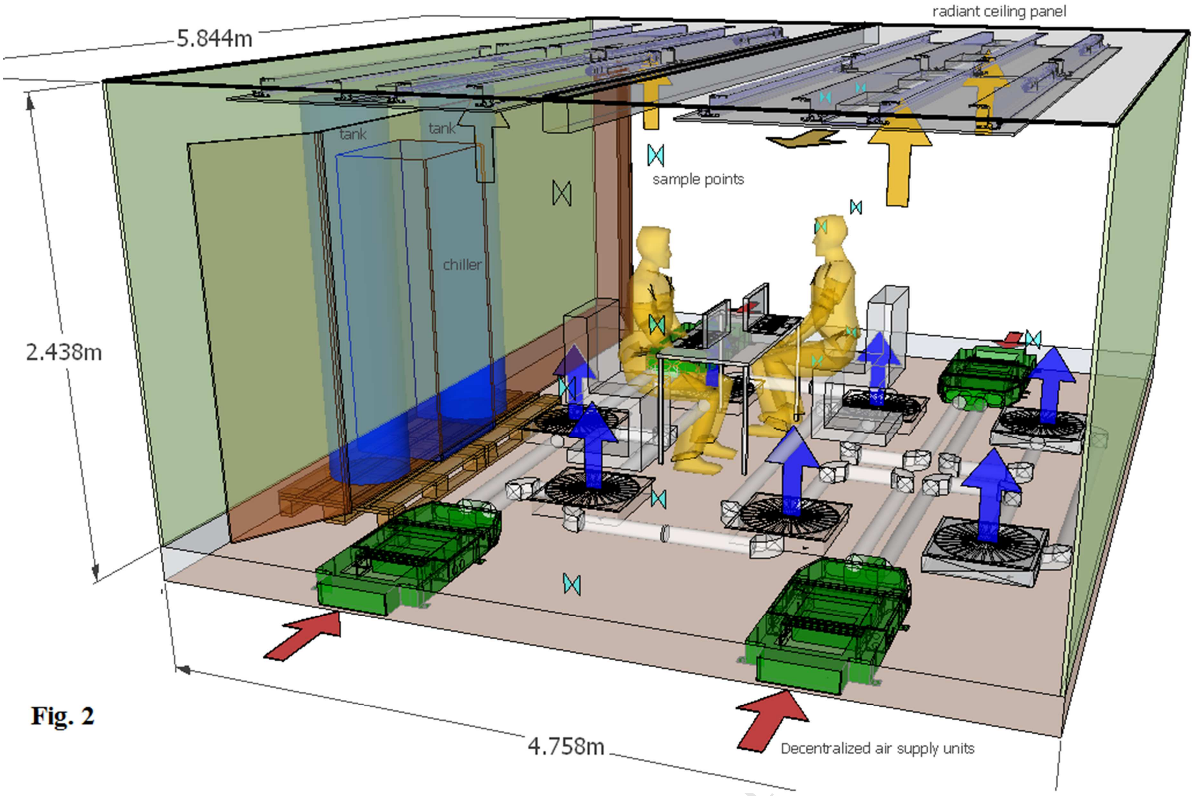
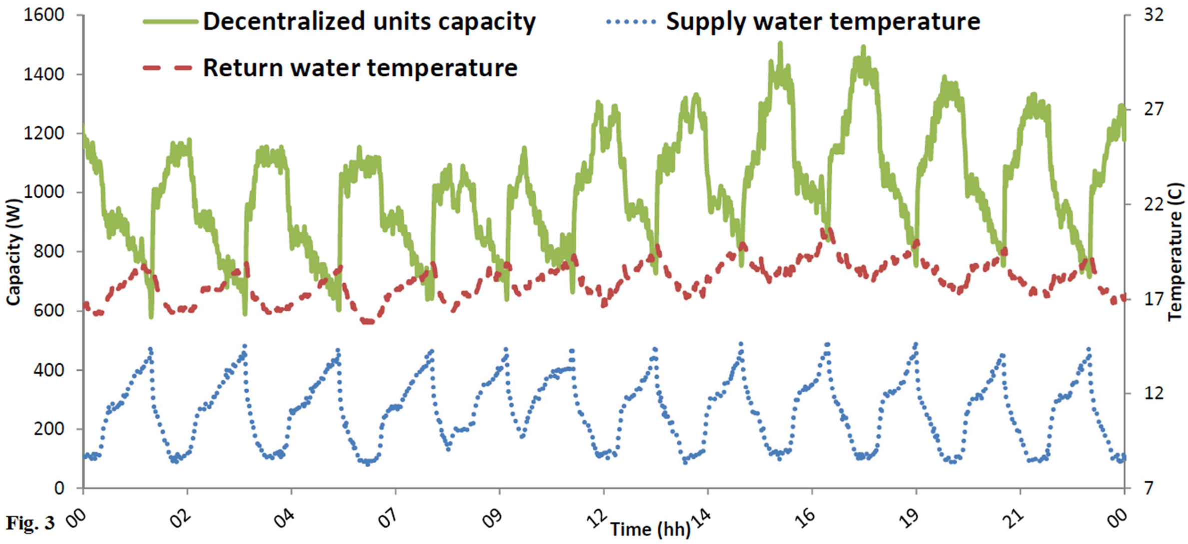

5.844m
radiant ceiling panel
tank
tank
sample points
chiller
2.438m
4.758m
Decentralized air supply units

Fig. 2



Decentralized units capacity
Supply water temperature
Return water temperature
Capacity (W)
Temperature (C)
Time (hh)
1600
1400
1200
1000
800
600
400
200
0
32
27
22
17
12
7
00
02
04
07
09
12
14
16
19
21
00

Fig. 3

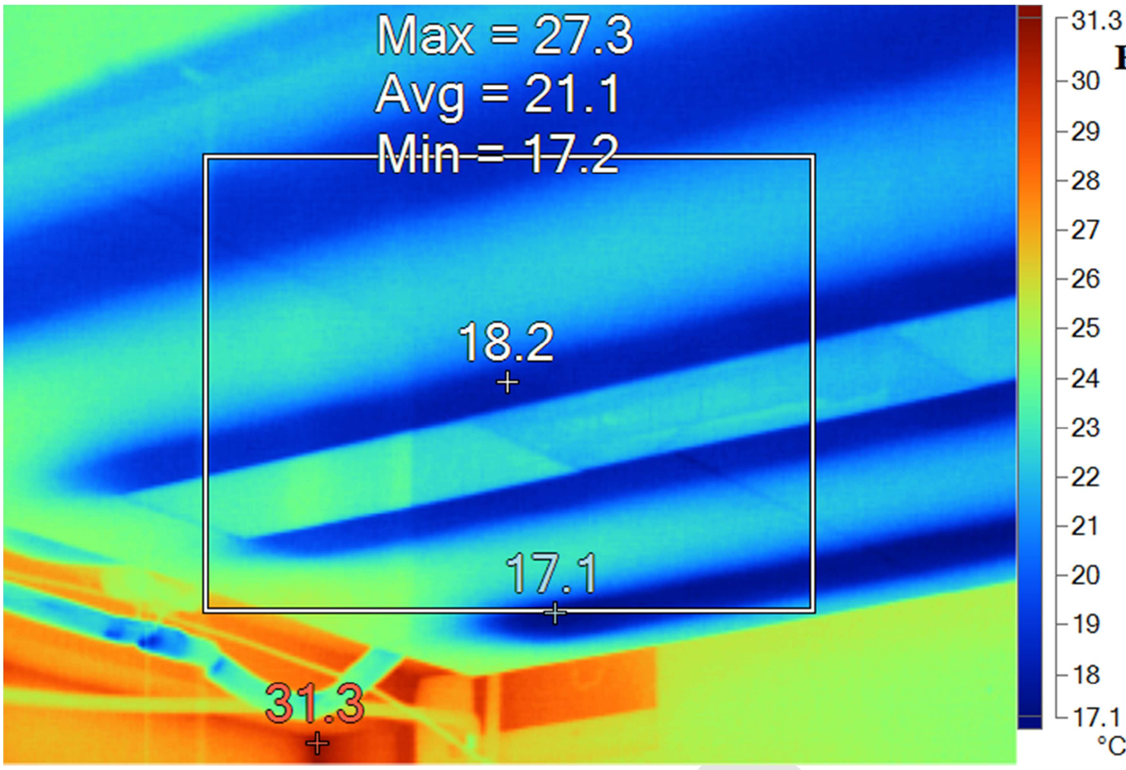

Max = 27.3
Avg = 21.1
Min = 17.2
18.2
17.1
31.3
31.3
30
29
28
27
26
25
24
23
22
21
20
19
18
17.1
°C

Fig. 4

Fig. 5

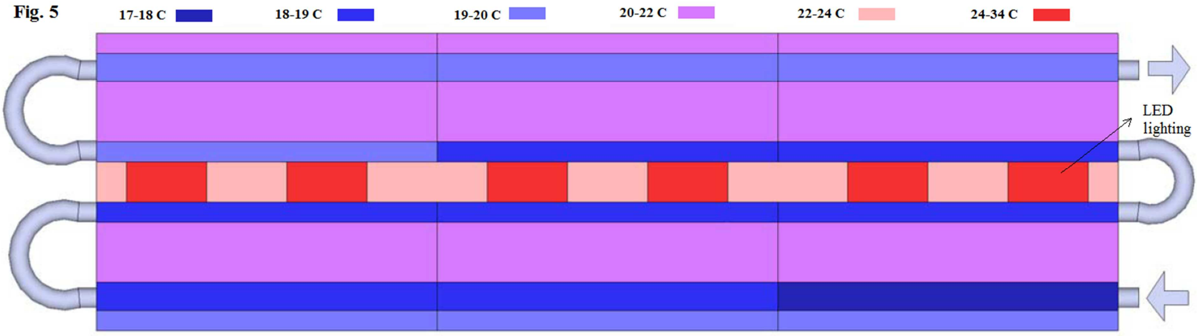


Fig. 6

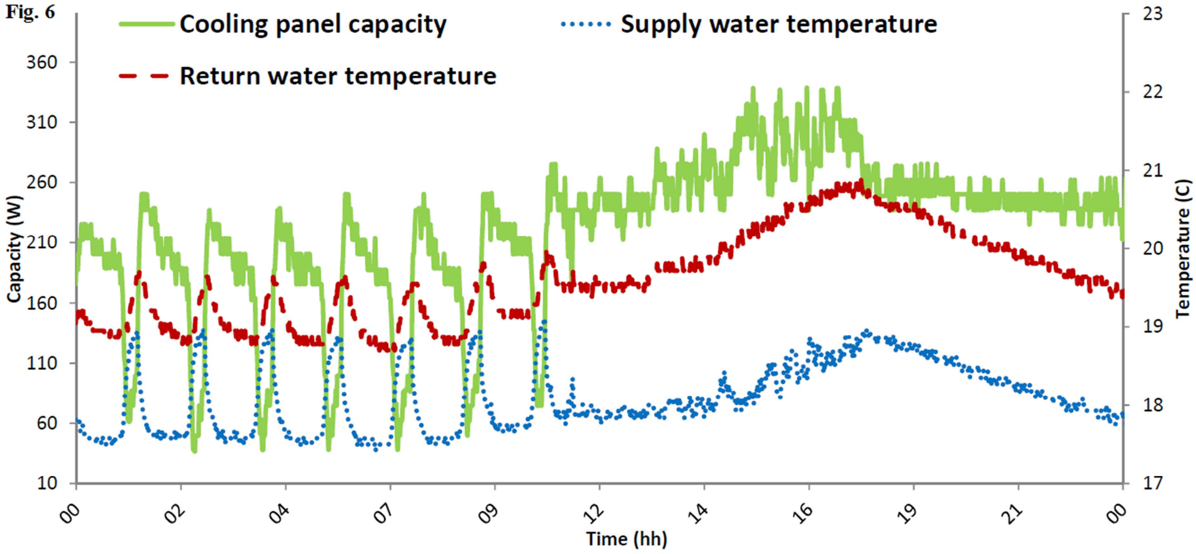

Cooling panel capacity
Supply water temperature
Return water temperature
Capacity (W)
Temperature (C)
Time (hh)
360
310
260
210
160
110
60
10
23
22
21
20
19
18
17
00
02
04
07
09
12
14
16
19
21
00

Fig. 7

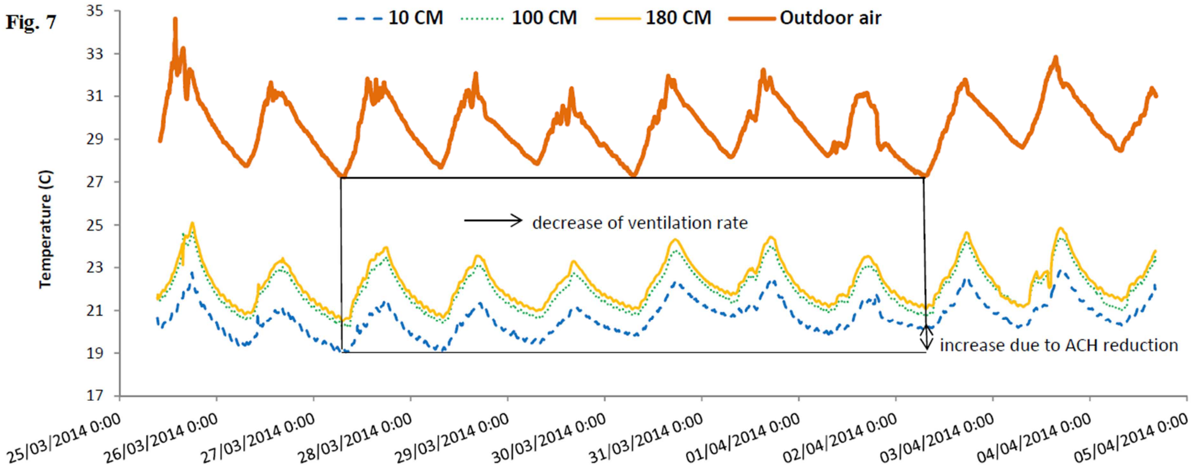
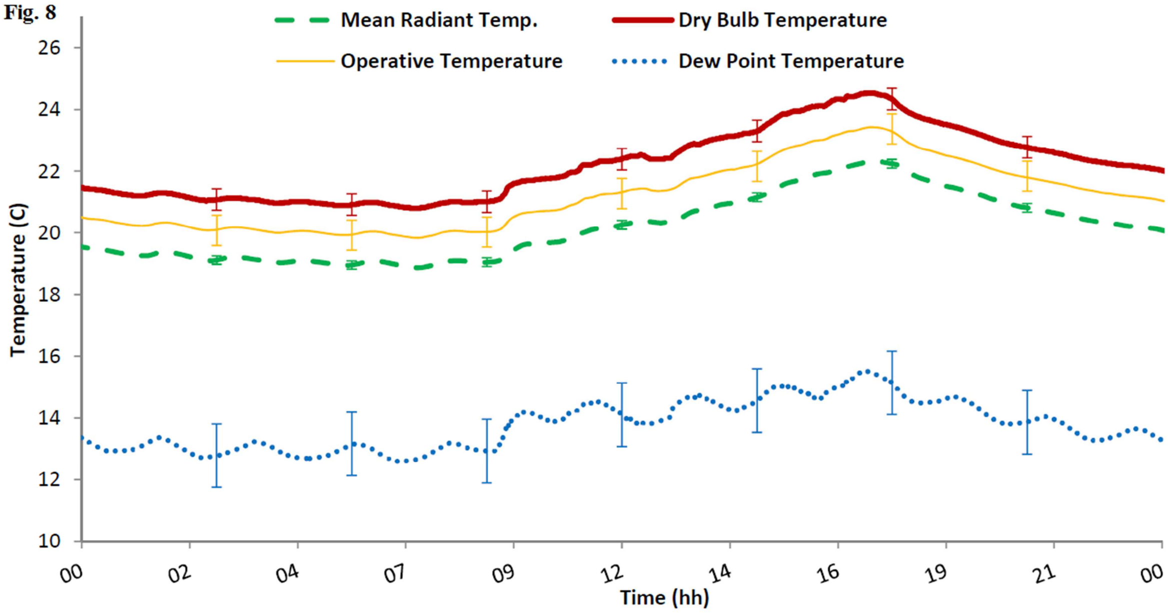

10 CM
100 CM
180 CM
Outdoor air
Temperature (C)
35
33
31
29
27
25
23
21
19
17
decrease of ventilation rate
increase due to ACH reduction
25/03/2014 0:00
26/03/2014 0:00
27/03/2014 0:00
28/03/2014 0:00
29/03/2014 0:00
30/03/2014 0:00
31/03/2014 0:00
01/04/2014 0:00
02/04/2014 0:00
03/04/2014 0:00
04/04/2014 0:00
05/04/2014 0:00

Fig. 8


Mean Radiant Temp.
Dry Bulb Temperature
Operative Temperature
Dew Point Temperature
Temperature (C)
26
24
22
20
18
16
14
12
10
00
02
04
07
09
12
14
16
19
21
00
Time (hh)

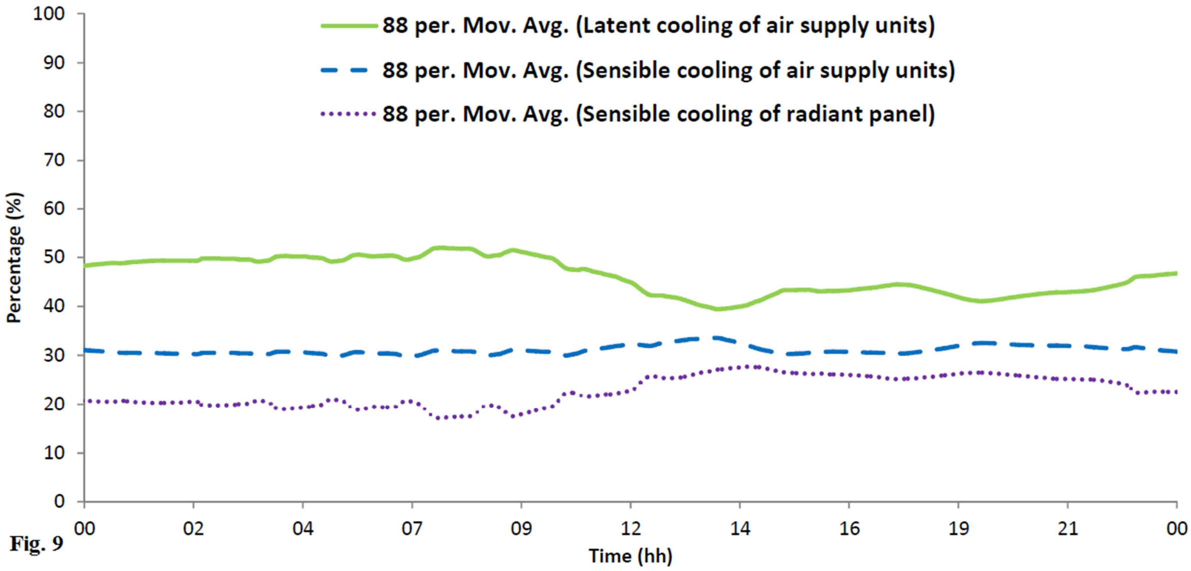
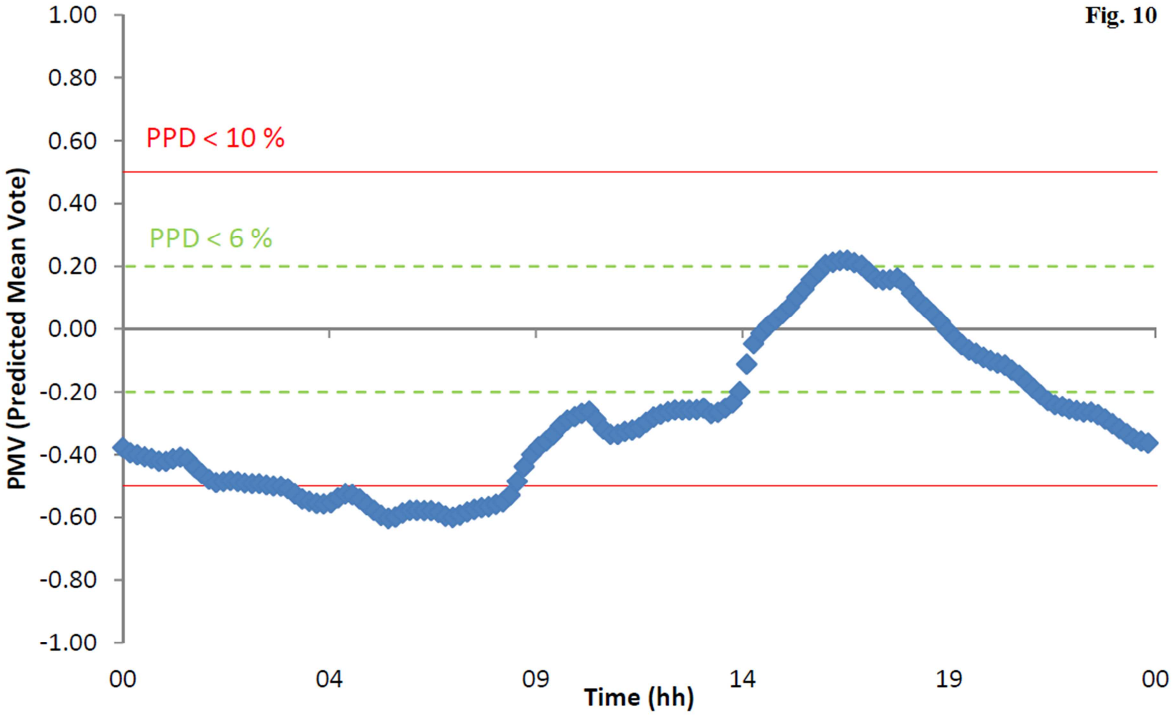
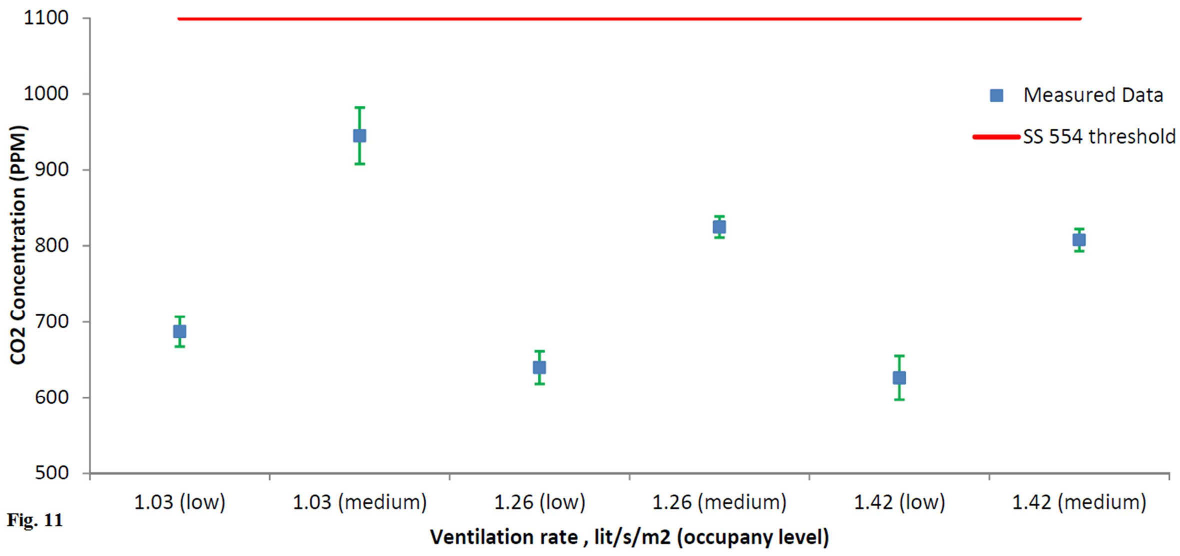

88 per. Mov. Avg. (Latent cooling of air supply units)
88 per. Mov. Avg. (Sensible cooling of air supply units)
88 per. Mov. Avg. (Sensible cooling of radiant panel)
Percentage (%)
100
90
80
70
60
50
40
30
20
10
0
00
02
04
07
09
12
14
16
19
21
00
Time (hh)

Fig. 9

Fig. 10


1.00
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
-1.00
PMV (Predicted Mean Vote)
PPD < 10 %
PPD < 6 %
00
04
09
14
19
00
Time (hh)



1100
1000
900
800
700
600
500
CO2 Concentration (PPM)
Measured Data
SS 554 threshold
1.03 (low)
1.03 (medium)
1.26 (low)
1.26 (medium)
1.42 (low)
1.42 (medium)
Ventilation rate , lit/s/m2 (occupany level)

Fig. 11

Dear Sir/Madam,

Editor of Building and Environment Journal,

The core finding of this research paper could be summarized as follows,

- Characteristics of DDOAS-RCS coupled systems in the tropics were analyzed in depth
- Impacts of main system related parameters on indoor air condition were discussed
- ventilation rate in DDOAS-RCS design needs to be higher than minimum requirements
- An automatic control is required to achieve thermal comfort in different conditions

Regards,

Esmail M. Saber